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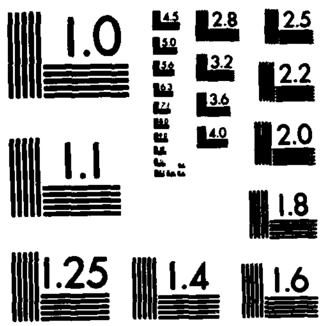

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REPORT SD-TR-84-52

AD-A148 694

Millimeter Wave Antenna Technology

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30 September 1984

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Prepared for

SPACE DIVISION
AIR FORCE SYSTEMS COMMAND
Los Angeles Air Force Station
P.O. Box 92960, Worldway Postal Center
Los Angeles, Calif. 90009

This report was submitted by The Aerospace Corporation, El Segundo, CA 90245, under Contract No. F04701-83-C-0084 with the Space Division, P.O. Box 92960, Worldway Postal Center, Los Angeles, CA 90009. It was reviewed and approved for The Aerospace Corporation by D. H. Phillips, Director, Electronics Research Laboratory. Lt Harold J. Morgan, SD/YKX, was the project officer for the Mission-Oriented Investigation and Experimentation (MOIE) Program.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER SD-TR-84-52	2. GOVT ACCESSION NO. AD-A148694	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) MILLIMETER WAVE ANTENNA TECHNOLOGY		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER TR-0084(4925-06)-1
7. AUTHOR(s) Robert B. Dybdal		8. CONTRACT OR GRANT NUMBER(s) F04701-83-C-0084
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Aerospace Corporation El Segundo, Calif. 90245		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Space Division Los Angeles Air Force Station Los Angeles, Calif. 90009		12. REPORT DATE 30 September 1984
		13. NUMBER OF PAGES 37
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Adaptive processing
Array antennas
Lens antennas
Millimeter wave
Multiple beam antennas
Reflector antennas

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Millimeter wave antenna technology has had a long history of development, and as millimeter wave systems evolve through planning to implementation, a significant amount of additional development work will be required. Millimeter wave antennas play a key role in the rationale for millimeter system designs because high spatial resolution can be achieved with modest physical dimensions. Reflector, lens, array, and horn technologies are surveyed.

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19. KEY WORDS (Continued)

20. ABSTRACT (Continued)

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Multiple beam designs and adaptive processing antennas are described because these technologies afford high leverage opportunities to enhance electronic survivability and to extend communication capabilities. Ancillary components, such as radomes, are a necessary part of practical antenna designs and are discussed in some detail. Originator-supplied keywords include: Array antennas, Lens antennas, Multiple beam antennas, and Reflector antennas.

PREFACE

A survey of this type necessarily draws on the efforts of many individuals and appropriate acknowledgment of all concerned is impractical. On a personal level, the author would like to acknowledge H. E. King for his interest and support spanning many years.

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I. INTRODUCTION

The expanded development of millimeter wave systems in recent years stems from improvements in component technology, wide spectral allocations to support high-data-rate users, spread-spectrum modems, and a multitude of small users, spectral crowding at lower frequencies, the desire for improved immunity to interference, and reduced sensitivity to propagation limitations compared with electrooptical systems. A key rationale for millimeter wave systems stems from a basic property of the antenna itself—a high degree of spatial resolution can be achieved from antennas with modest physical size. The narrow beamwidths can be used to optimize communications to particular user communities, reject interference in the receive mode, enhance LPI (low probability of intercept) performance in the transmit mode, and minimize multipath effects during low angle operation.

A broad range of demonstrated antenna techniques provides a database to project the performance capabilities of future designs. However, future development is required to transcribe the well developed microwave technology into practical millimeter wave implementations. Two generic problems exist for millimeter wave antenna development: the antenna system must be manufactured with more stringent mechanical and electrical tolerances compared to lower frequency designs and the sensitivity to RF losses increases with increasing frequency; e.g., straight waveguide at 90 GHz has a 1 dB/ft attenuation. While greater bandwidths are allocated at millimeter wavelengths, the percentage bandwidths may be smaller; e.g., 500 MHz at 7/8 GHz represents a 6.6 percent value, whereas 2 GHz at 44 GHz represents a 4.5 percent value. Generally, the degree of difficulty in component development is related to the percent bandwidth, which may be smaller at millimeter wave frequencies. Frequency allocations may be found in Ref. 1.

This paper provides an overview of millimeter wave antenna technology. A more detailed technology survey, which specifically addresses antennas for satellite communications, may be found in Ref. 2. Reflector, lens, array, and horn technology will be surveyed in turn. On a system level, multiple beam

antennas and adaptive processing techniques offer particularly high leverage opportunities to enhance communications capabilities. Ancillary components, such as radomes, are worthy of discussion because of their importance in practical designs.

II. MILLIMETER WAVE ANTENNA STATUS

This section surveys the development status of millimeter wave antennas. The compact physical size of antennas with particular gain levels is illustrated in Fig. 1 for a typical 55 percent antenna efficiency. The small physical size provides tractability to meet system objectives which would be difficult to achieve at lower frequencies.

A. REFLECTOR DESIGNS

Reflector antenna technology has achieved the highest level of development for high gain applications at millimeter wavelengths as selected developments will illustrate. The radio astronomy community has been particularly active in the demonstration of large millimeter wave antennas and construction techniques which achieve the requisite precision.

One of the earliest high gain antenna demonstrations is the 15 ft reflector at The Aerospace Corporation.[3] This antenna, pictured in Fig. 2, has been in operation since 1963 and has been used at frequencies as high as 220 GHz.[4] The measured gain of the antenna at 94 GHz is 70.5 dB, which corresponds to a 55 percent aperture efficiency, which is typically used in system estimates.

A key requirement to achieve this gain performance is a precise reflector surface. The requirements for mechanical precision are to first order given by the analysis developed by Ruze.[5] The gain G of a circular reflector of diameter D is given by

$$G = \eta(\pi D/\lambda)^2 e^{-(4\pi\varepsilon/\lambda)^2} \tag{1}$$

where η is the antenna efficiency, which includes blockage, spillover, mismatch, taper, and cross polarization losses, λ is the operating wavelength, and the exponential term accounts for the gain loss due to the rms roughness ε. The precision of manufacture D/ε is the usual measure of reflector quality. This analysis was used to predict the gain characteristics of the

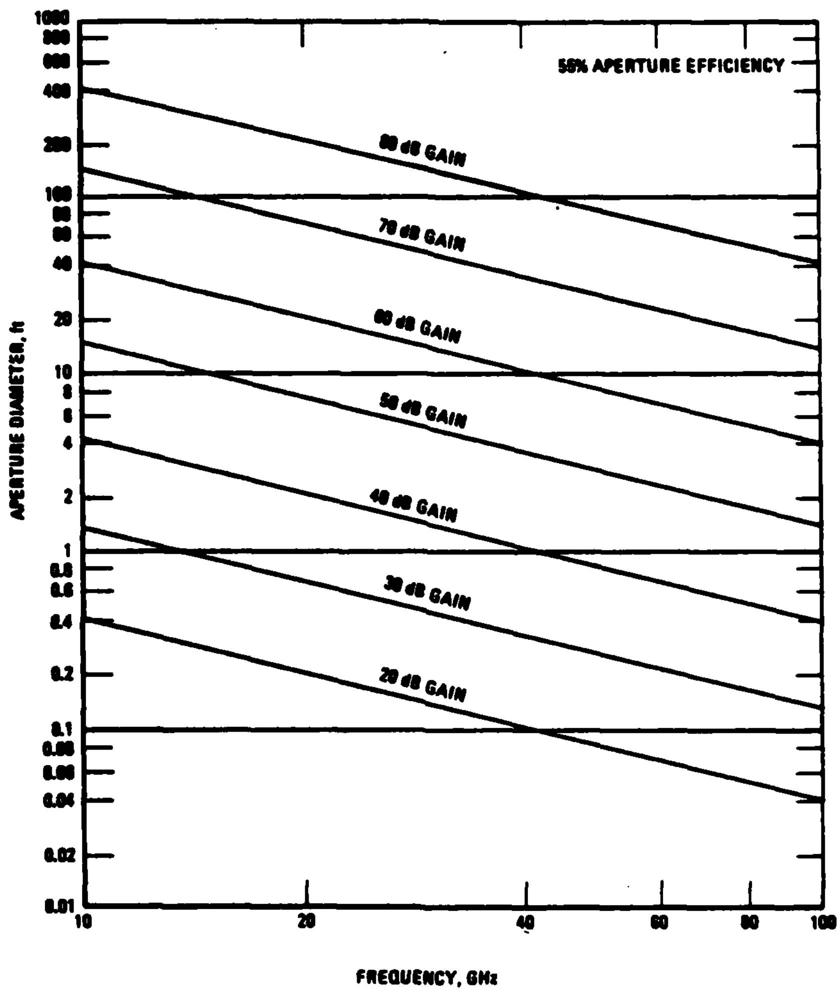


Fig. 1. Representative Antenna Dimensions for a Given Gain Level as a Function of Frequency

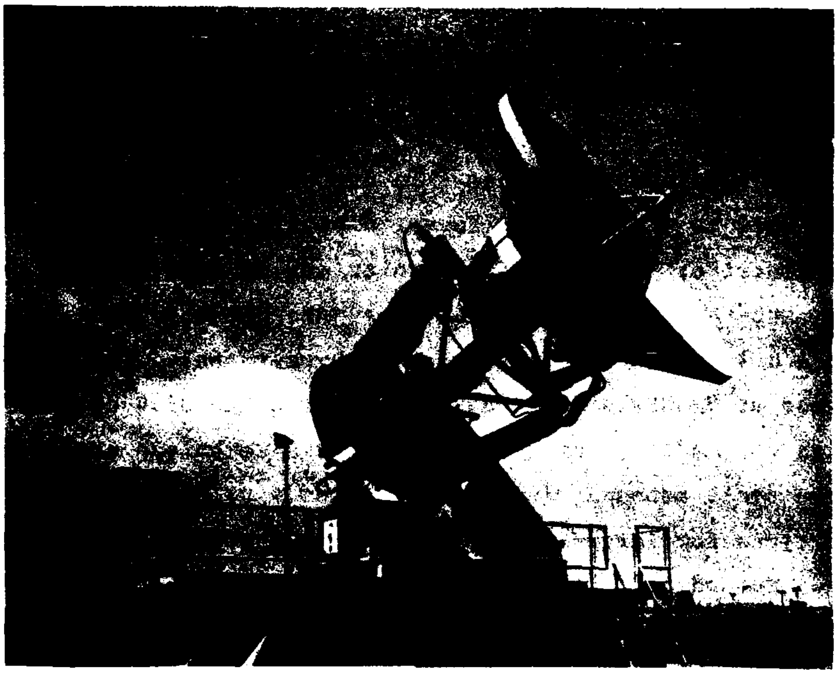


Fig. 2. 15 ft Millimeter Wave Antenna at The Aerospace Corporation

15 ft antenna as shown in Fig. 3. The rms roughness of this antenna varies with elevation angle, an effect caused by gravitational deformation. More detail on gravitational limitations and structural techniques may be found in Ref. 6.

Antennas with such high gain levels offer a technology base for fixed ground terminals associated with high data rate communications with minimal weather outage. Other applicatons, particularly in the tactical regime, have more modest gain requirements or size restrictions that dictate smaller reflector dimensions. Present commercially available reflectors can be obtained with values of D/ε of 2×10^4 for diameters up to 4 ft. Cassegrainian reflector systems are particularly popular because the length of waveguide to the feed and its associated attenuation are minimized.

Another interesting development in reflector geometries is the demonstration of low sidelobe techniques. In one demonstration, absorber-lined tunnels were used to minimize spillover, direct feed radiation, and edge diffraction contributions to the pattern at angles removed from the main beam.[7] The patterns shown in Fig. 4 illustrate the reduction in sidelobe levels when a 6 in reflector is surrounded by a tunnel. These measurements were performed at 92 GHz and no degradation from the 39.4 dB gain level was observed with the addition of the tunnel. This technique can be effectively used with the small antenna size at millimeter wavelengths; a tunnel with these proportions for larger reflector diameters would become physically untractable. The edges of the tunnel are rounded to further reduce diffraction effects. This technique is effective when the radius of curvature of the edge is several wavelengths, a reasonable dimension at these frequencies.

Another low sidelobe demonstration at millimeter wavelengths uses an offset reflector fed by a corrugated horn.[8] This configuration also uses an absorber-lined tunnel to control the sidelobe levels and is advantageous because feed blockage contributions to the pattern are not present. The measured pattern given in Fig. 5 illustrates the capability to achieve very low sidelobe levels at wide angles from the main beam.

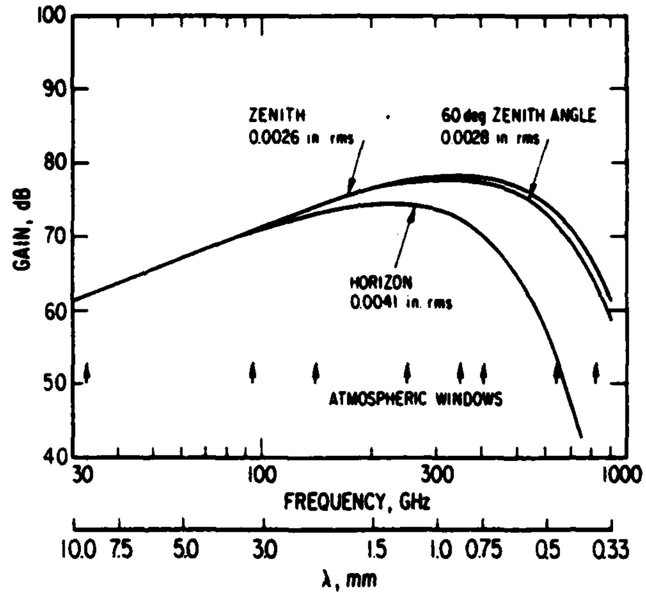
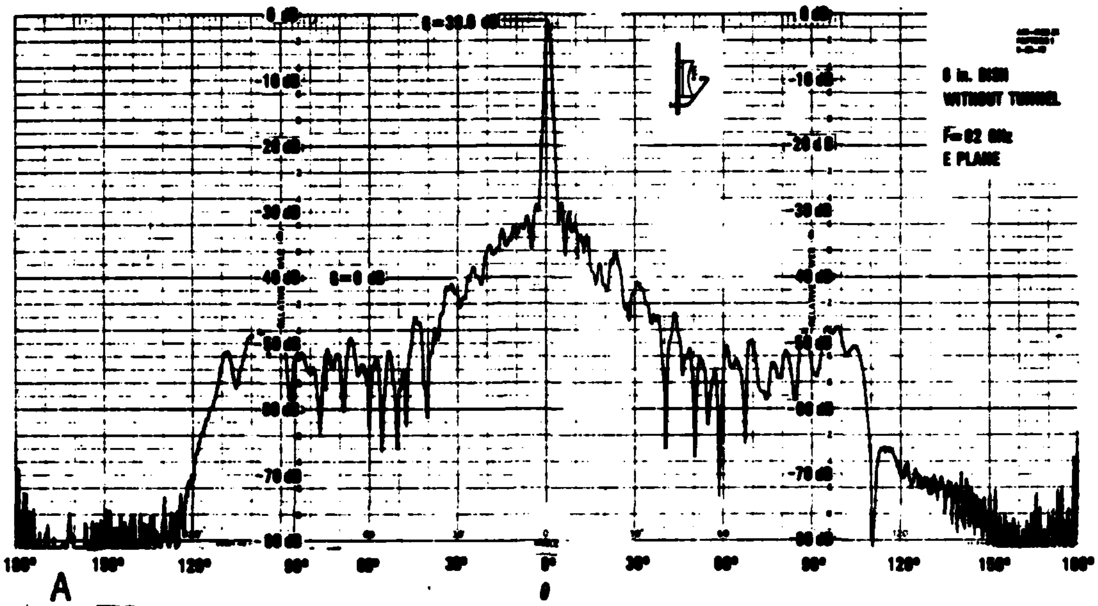


Fig. 3. Calculated Gain for The Aerospace Corporation Antenna Which Indicates Tolerance Loss



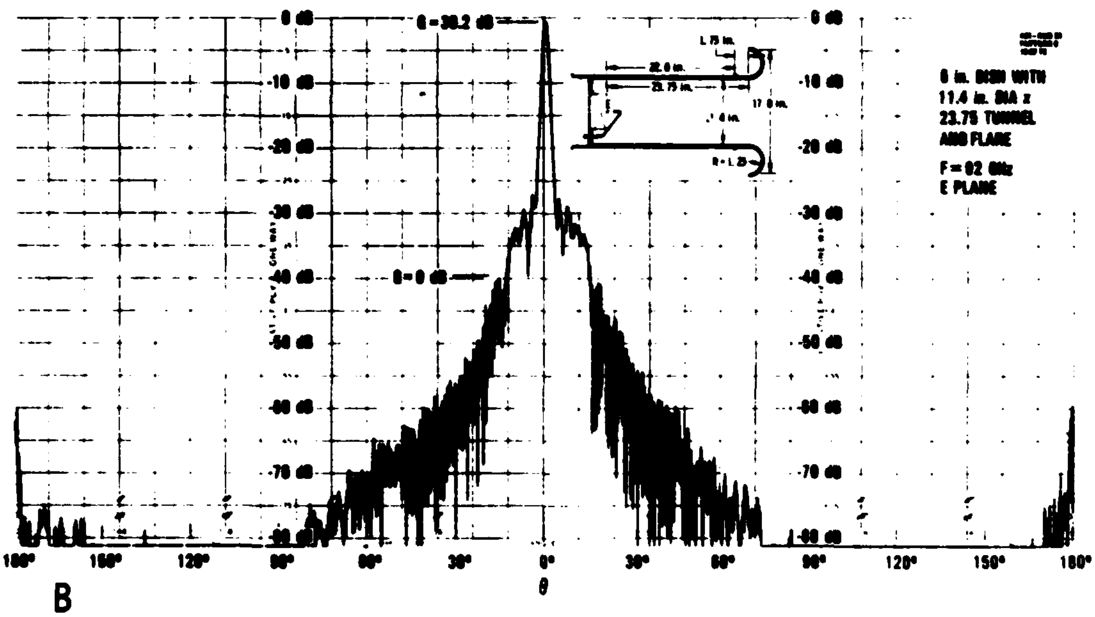
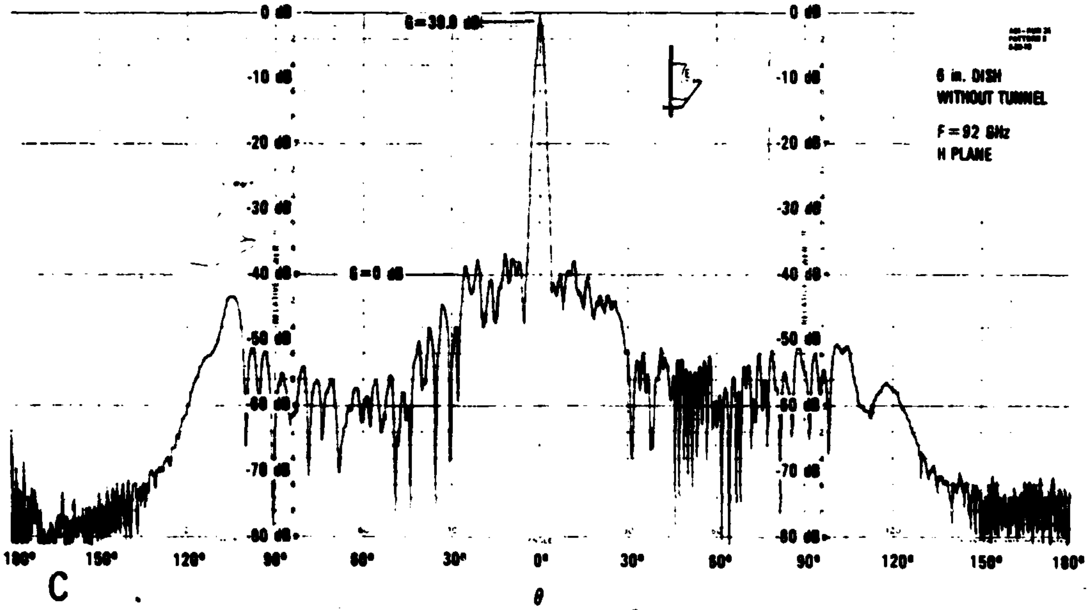


Fig. 4. 92 GHz Measurements of a 6 in Reflector with and without an Absorber-Lined Tunnel. (a) E-plane without tunnel. (b) E-plane with tunnel.



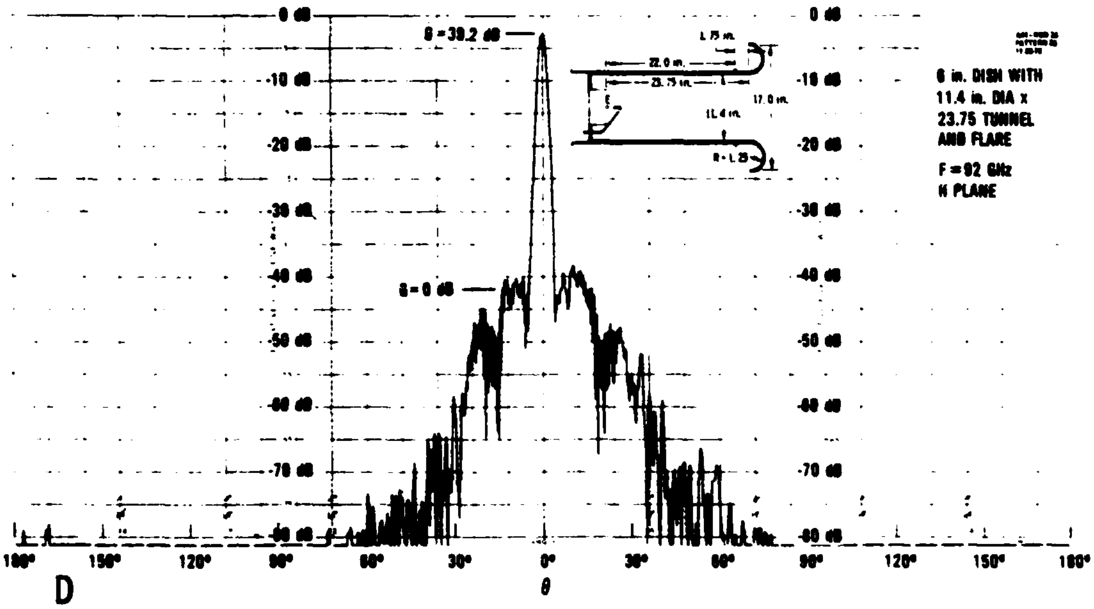


Fig. 4. (Cont'd). (c) H-plane without tunnel. (d) H-plane with tunnel.

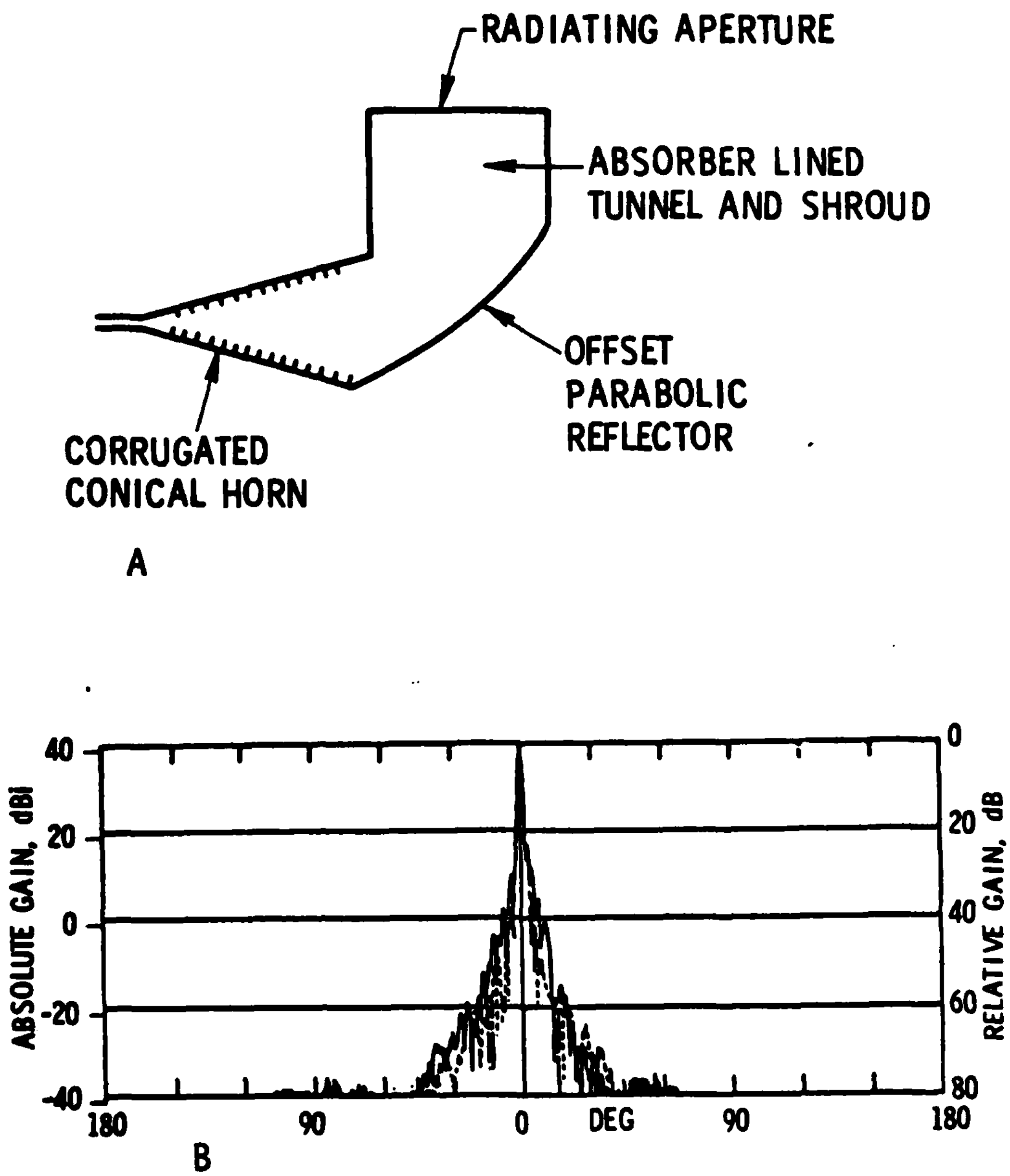


Fig. 5. NRL Low Sidelobe Antenna (after Ref. 8). (a) Antenna configuration. (b) Measured principal plane patterns.

While reflector antenna technology is well established at millimeter wavelengths, several issues remain to be addressed. Further development and demonstration of feed systems for tracking are warranted. The development of feed systems for optimum illumination for widely spaced receive and transmit frequencies should be pursued. The integration of electronics with the feed elements would result in increased RF efficiency.

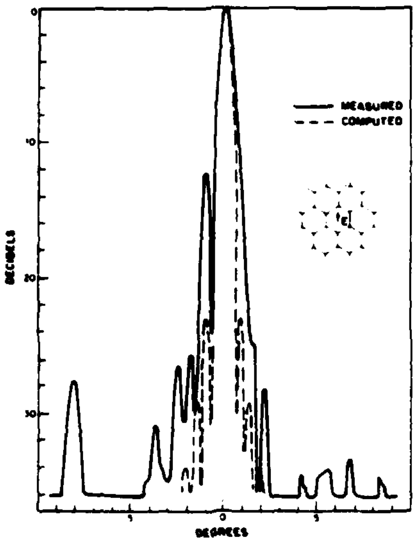
B. LENS DESIGNS

Lens antennas are a second high gain technology. Lens designs avoid blockage effects and achieve good scan performance, a factor which results in their popularity for multiple beam applications. In their design, care must be exercised to minimize reflection losses at the lens surfaces.

Waveguide lens technology uses waveguide elements as a constrained refractive media. The phase velocity in waveguide exceeds the speed of light, and the lengths of waveguide between the lens surfaces are chosen to produce a collimated aperture distribution. The waveguide is a dispersive media, i.e., the phase velocity varies with frequency. As a consequence, the operating bandwidth of these designs is limited. Zoning techniques, i.e., truncating the waveguides to achieve the required aperture distribution in a modulo 2π sense, can actually enhance the bandwidth of the lens as described in Ref. 9.

An example of waveguide lens technology is an unzoned lens configuration measured at 55 GHz.[10] A 24 in diameter lens was constructed from a commercially available honeycomb media, which highlights a tolerance problem for these designs. The mechanical tolerance of the honeycomb material was not sufficiently precise and consequently, index of refractions distort the aperture phase distribution which produces the high sidelobes shown in Fig. 6 and reduced aperture efficiency.

Homogeneous dielectric lens designs become feasible because the compact size of millimeter wave antennas leads to a viable design. At lower frequencies, this design is often impractical because the larger dimensions result in escessive lens weight. Moreover, such designs can also be configured so that the outer surface of the lens also serves as a radome, a significant advantage for some applications. An example of this technique, a 6 in diameter lens



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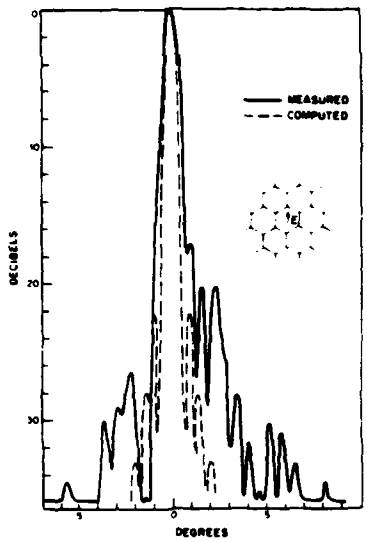

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Fig. 6. Principal Plane Patterns of Waveguide Lens with Phase Error (after Ref. 10). (a) E-plane. (b) H-plane.

constructed from Rexolite,[11] uses a dual frequency feed and operation at 20/44 GHz is demonstrated. Without zoning,the dielectric lens is a true time delay design capable of broadband operation.

Another class of lens designs uses an inhomogeneous index of refraction to achieve lens collimation. A geodesic Luneburg lens, demonstrated in the late 1950's at 70 GHz[12] uses a 2-dimensional parallel-plate construction whose contours are selected to provide an effective index of refraction.[13] The lens produces a fan beam which illuminates a cylindrical parabolic reflector. Azimuth steering was accomplished by the selection of the appropriate multiple beam feed, while elevation steering was implemented by properly positioning the parabolic reflector. In general, inhomogeneous lens designs offer the potential for wide angle beam steering with uniform beam quality throughout the scan region.

C. ARRAY DESIGNS

Millimeter wave array antennas have lagged the development of other techniques. This situation stems from the lack of development and demonstration of phase shifter technology, the high sensitivity to RF losses in phase shifters and combiner circuitry, the tight packaging dictated by interelement dimensions, and the feasibility of mechanical scanning, which results from the compact antenna size.

Waveguide slot arrays have been demonstrated at millimeter wave frequencies. These simple array designs are basically scaled from lower frequency technology.[14] Such arrays can be mechanically pointed and monopulse processing techniques have been demonstrated to achieve a tracking capability.

Active array techniques are currently undergoing development effort to extend the performance of this technology. Active antenna array techniques coupled with the low power levels of solid-state transmitting devices offer the significant potential benefits to combine a large number of transmitting amplifiers to achieve a high transmit power level and achieve graceful degradation with the failure of individual transmitting elements. However, the achievement of these potential benefits must also address the amplitude and phase tracking between array elements, which is aggravated by the thermal

problem which results from the small interelement spacing. Array elements must be spaced not much greater than a half wavelength apart to avoid the appearance of grating lobes in the pattern, and at millimeter wavelengths, this spacing requirement results in very small dimensions.

Current research efforts in array technology address fabrication techniques to integrate antenna elements and electronics. The goal of these efforts is to develop monolithic assemblies in order to achieve reproducibility, larger scale economics, minimal RF losses, and a reduction in the number of connecting junctions. A variety of applications from antenna feed systems to conformal array configurations are being examined. While basic technology demonstrations and fabrication methods are being developed, a significant amount of effort is still required to achieve practical system designs.

D. HORN DESIGNS

Another technology which has had significant development is horn antennas. The compact size of millimeter antennas allows the construction of horn antennas up to about a 30 dB gain limit. The construction of these antennas is straightforward and a wide variety of designs have been demonstrated.

Standard gain horn antennas are a stock commercial item throughout the millimeter wave spectrum and their calibration is well established.[15] Dielectric lens techniques have also been used to correct the aperture phase distribution[16] to achieve high gain with a compact length.

While ordinary horns are simple to construct, their performance is limited by high E-plane sidelobes and a beam pattern which is not rotationally symmetric when equal aperture dimensions are chosen in both planes. As described in Ref. 17, a variety of approaches have been used to overcome these limitations, and the majority of these techniques have been demonstrated at millimeter wavelengths. Diagonal and dual mode horn designs have been developed inhouse at Aerospace. The 6 in dish, whose patterns are shown in Fig. 4, uses a diagonal horn feed. A dual mode horn, whose patterns are given in Fig. 7, has also been demonstrated at 94 GHz. These horns were fabricated by electroforming copper over a mandrel, a technique which produces a precision product. A corrugated horn whose pattern is shown in Fig. 8, has also been constructed using a shim assembly for operation at 92 GHz.

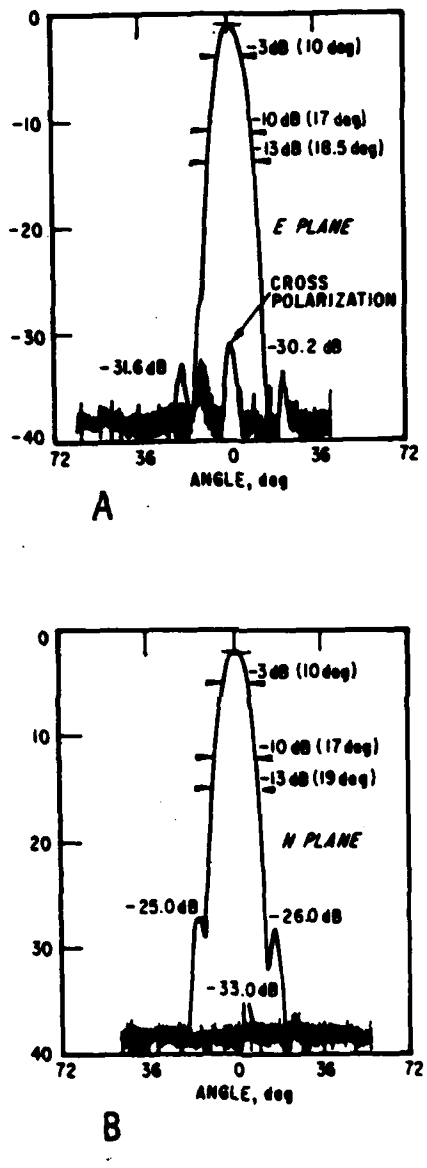

Fig. 7. 94 GHz Dual-Mode Horn Patterns. (a) E-plane. (b) H-plane.

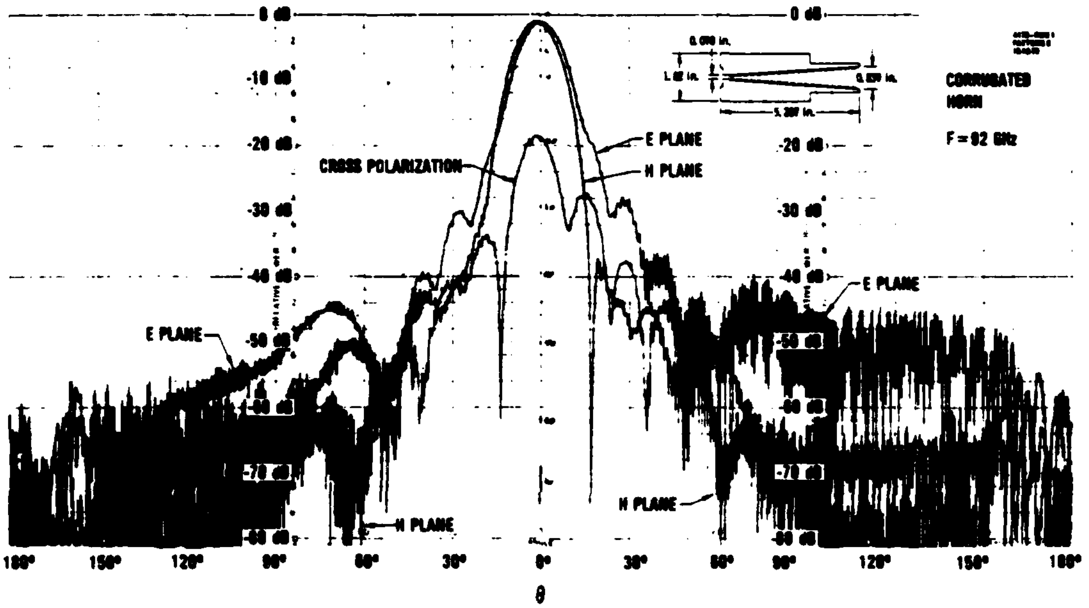

Fig. 8. 92 GHz Corrugated Horn Patterns

III. SYSTEM CONSIDERATIONS

Thus far, antennas have been discussed on a component level. The demands for future communication systems which afford both electronic survivability and expansion of service to small users dictate a discussion of antennas on a system level. Future designs will capitalize on multiple beam antennas to expand communication capabilities and adaptive antenna technology to counter intentional and unintentional interference.

A. MULTIPLE BEAM ANTENNAS

The expansion of communication capability for satellite segments can be significantly enhanced through the use of multiple beam designs. Multiple beams can be used to synthesize coverage to particular user communities, reuse the allocated spectrum simultaneously for different geographic locations, and change the pattern coverage to accommodate varied user requirements. The significant advantages to synthesizing the coverage area from the multiple beam collection include the maximization of gain to the users and the natural rejection of interference beyond the desired coverage area which results from the antenna sidelobe response. An earlier survey paper[18] describes multiple beam systems in more detail.

Multiple beam systems place the following requirements on the antenna development. The antenna hardware must generate beams with good pattern performance over the desired field of view; for the antenna design, this requirement is equivalent to the development of an antenna with good scan performance in terms of both pattern characteristics and minimal gain loss with scan variations. The sidelobe response of the antenna should be low to minimize coupling between beam positions and to maximize the immunity to interference. The trend for domestic satellite systems is to use frequency reuse, which, in that application, means the transmission of individual channels on orthogonal polarizations. This requirement results in the desire to minimize the cross polarization in the antenna beams to avoid interchannel interference.

A significant amount of development work has been done in recent years to explore suitable antenna technology for multiple beam designs. At millimeter wavelengths, logical technologies include offset reflector and lens designs.

One example of offset reflector designs, reported in Ref. 19, was demonstrated at 100 GHz and uses a Cassegrainian geometry illustrated in Fig. 9. The variation in gain and beamwidth characteristics with scan angle are shown in Fig. 10, which serves to illustrate the previous comments on antenna requirements. The narrow beamwidth of this design would require a large number of beams to provide coverage over the earth's surface.

In addition to the antenna, significant efforts are needed in future developments to derive suitable beamforming networks to appropriately combine the multiple beams generated by the antenna. A multiple beam system inherently affords a substantial number of ways to combine the individual beams; however, this inherent flexibility is limited by the design complexity of the beamforming networks. In addition, the design complexity of the beamforming networks must be tempered by operational requirements. For example, domestic systems typically have fixed user locations and combining circuitry for the multiple beams similarly has relatively fixed requirements to serve the appropriate geographic areas. In contrast, military systems require a significant variation in coverage requirements to accommodate changing communication needs. Thus, the nature of military communications dictates a more general beamforming network than domestic communication systems.

Beamforming for the receive mode may be done at either the RF or IF levels. RF beamforming networks have had a long history of development; for example, variable power divider networks have been used[20] for a variable coverage mode. The beam patterns can vary between a single beam response to the response for the full coverage area achieved when all the beams are added together. In addition, certain beam positions can be deleted when geographic areas are devoid of users to obtain higher gain performance or when interference is present. At any given time, only a single beam pattern consisting of the selected combination of multiple beams is formed by the antenna. The extension of this approach to multiple beam operation for the system having

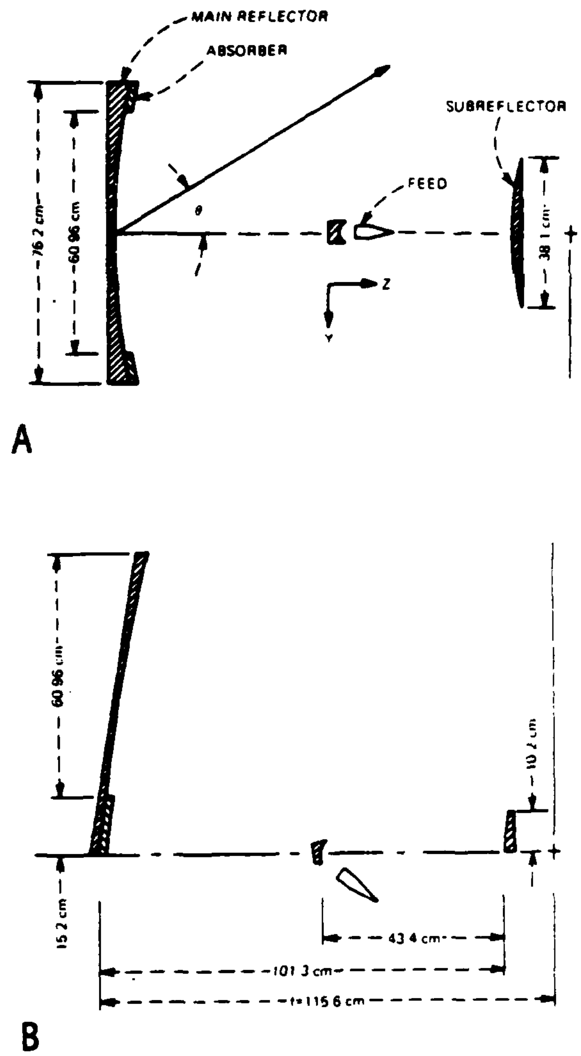

Fig. 9. Geometry of BTL Offset Reflector. (a) Plan view. (b) Side view. (Reprinted, with permission, from the Bell System Technical Journal, copyright 1977, AT&T.)

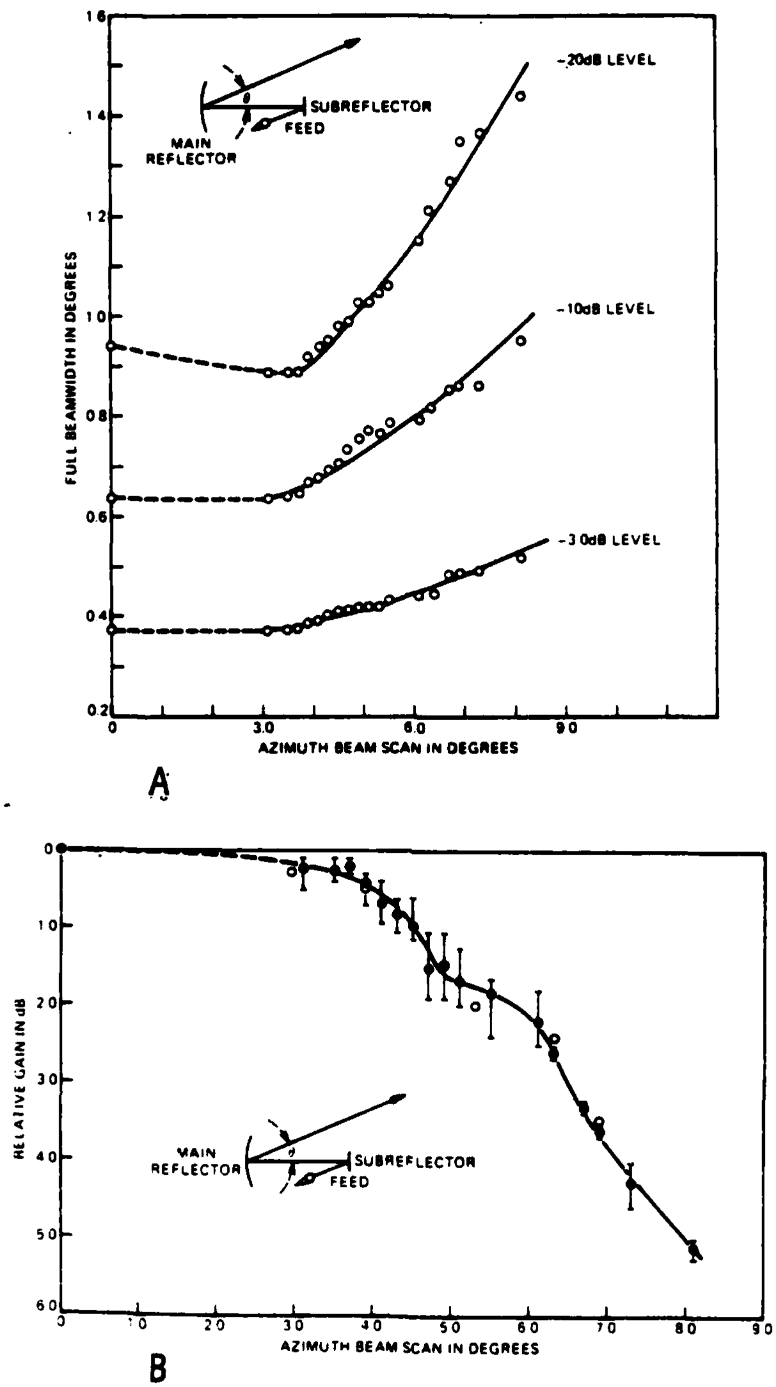

Fig. 10. Pattern and Gain Characteristics of the BTL Offset Reflector. (a) Pattern variation with scan. (b) Gain variation with scan. (Reprinted, with permission, from the Bell System Technical Journal, copyright 1977, AT&T.)

several beam patterns at any given time would require a more general beamforming network.

The alternative to RF beamforming is to combine the outputs of the individual beams at IF frequencies. Some conceptual ideas for IF beamforming may be found in Ref. 18. Such an approach has the advantage that the G/T ratio can be established without incurring the losses associated with the beamforming network, which can be substantial at millimeter wave frequencies. This mode of operation can incorporate spectral filtering so that different beam patterns can be generated for different operating segments of the allocated spectrum. The combination at IF frequencies also provides a logical transition for the incorporation of adaptive processing. In addition, redundancy can be incorporated into the beamforming networks to enhance system reliability. The IF beamforming approach does require care in matching the amplitude and phase tracking between channels; however, because low level electronics are involved and the physical dimensions between channels are greater than those for an array, the amplitude and phase matching requirements may be more tractable than an active transmit array. The development of IF beamforming networks is envisioned as a logical means to exploit the inherent flexibility of multiple beam designs in future efforts.

Thus far, beamforming networks for the receive mode have been discussed. Beamforming networks for the transmit mode also require significant effort. Solid-state amplifier chains which are connected to each feed element and are powered to service the desired coverage area at any given time present the greatest opportunity to avoid RF switching losses. Certain critical beam positions can be protected with redundant amplifiers. The sensitivity to RF losses at millimeter wave frequencies presents significant challenges to develop efficient beamforming networks for the transmit mode.

The operational use of multiple beam antennas will present some interesting problems beyond the required technology developments. The command, control, and timing of the users, particularly as their numbers increase, will be essential to the practical utilization of these designs.

B. ADAPTIVE ANTENNA PROCESSING

Another system area which will have a significant application for future communication designs is adaptive interference rejection for the receive mode. A broad range of applications from satellite segments to small tactical users can achieve higher degrees of electronic survivability. A significant amount of effort has been devoted to the development and demonstration of such systems; Ref. 21 provides a basic discussion of these techniques.

The maximum protection from interference results from the use of spread-spectrum waveforms and an antenna which uses passive sidelobe control techniques with adaptive processing to further reduce interference power. Millimeter wave systems are particularly advantageous in their ability to exploit these techniques. Wide bandwidth allocations are available to effectively utilize spread-spectrum modems. The compact size of millimeter wave antennas permits the use of passive sidelobe control techniques within practical size constraints, as previously discussed. In many cases, the passive reduction of antenna sidelobe levels may be effective in the reduction of the number of interference sources, and the requirements for adaptive processing are reduced to the cancellation of the remaining interference sources. Moreover, the high degree of spatial resolution achieved by millimeter wave antennas offers the potential to cancel interference which arrives from directions which are close to the directions subtended by the desired user community. The ability to reject interference closely spaced to desired users depends on the aperture size in wavelengths, a compact physical size at millimeter wave frequencies.

The bandwidth of adaptive processing systems is limited because the frequency response for the antenna elements containing the adaptive control does not match the frequency response of the antenna elements configured for the desired signal reception. In a fully adaptive array, the frequency response difference results from the frequency scanning properties inherent in array designs. In a sidelobe canceller design, the frequency response of the main antenna differs from the auxiliary antenna elements used for the cancellation. The dispersion in the antenna, i.e., the frequency response

differences, results in the bandwidth limitation for adaptive cancellation. Tapped delay line techniques have been used to extend the bandwidth performance of adaptive circuitry. An interesting problem for future efforts is the development of antenna designs which are optimally suited to interface with adaptive processing systems.

IV. ANCILLARY EQUIPMENT

The development of ancillary equipment related to the antenna is also important for a practical antenna system. In many applications, the antenna must be protected from its operating environment by a radome. In addition, the interface between the antenna and electronics may require RF components which are an integral part of the antenna system.

A. RADOME CONSIDERATIONS

In some applications, e.g., aircraft, a radome to protect the antenna is mandatory, whereas in other applications, e.g., a tactical earth terminal, a radome is not strictly required but may be used, for example, for economic reasons. The cost of a positioner and servo drive capable of minimal pointing variations during wind loading may exceed the price of a radome and a less rugged positioner system.

The electrical performance of a radome at millimeter wave frequencies is complicated by both the tolerance requirements associated with the small wavelengths and in some designs, the requirement to operate at widely spaced frequencies, e.g., 20/44 GHz. In most cases, the required mechanical integrity dictates a radome which is multiple wavelengths in thickness.

Several demonstrations of millimeter wave radomes have been conducted to date. A large radome for a reflector antenna developed for 707 class aircraft[22] uses a sandwich construction, and calculated and measured radome efficiencies are presented. For higher performance aircraft, radomes with less protrusion are required; the dielectric lens described earlier[11] was motivated by this consideration. Another severe environment for an antenna is a submarine. A bell jar radome for this environment was described in Ref. 16. A more detailed description of the electrical performance of radomes for a submarine environment may be found in Refs. 23 and 24. These studies have particularly delved into antenna sidelobe increases induced by the radome structure.

More conventional radome designs use space-frame construction to protect the antenna. This technology is well developed for millimeter wave operation. The radome affords protection from wind loading effects and, thus, the structural requirements of both the reflector and its positioner are reduced. Similarly, the power and response speed for the positioner servo are minimized when corrections for wind gusts are not required. Suitable radome material has been developed for a wide range of frequencies. Operation at widely separated frequencies results in some compromises in radome efficiency. The decision for the use of a radome primarily rests on the requirement to operate in a specified wind speed and the associated margin for pointing losses. Lower gain antennas can generally be used without a radome.

A negative aspect for radome usage, which is sometimes overlooked in link budgets, is the loss in gain and the increase in noise temperature which result when rain wets the radome surface. The gain loss depends on the water distribution, and in addition, the sidelobe levels are generally increased when the radome is wet. When the water sheets to form a uniform layer, the water may be viewed electrically as an additional layer on the radome, and for a given layer thickness, the constitutive parameters of water may be used in a transmission line model to estimate the effect of the water on radome efficiency. In this case, the effect of the wet radome is principally gain loss caused by increased mismatch levels accompanied by a minimal sidelobe level increase. Alternatively, the radome surface may be treated to repel the water, and rivulet flow results. Since the water is more randomly distributed, the gain loss is less severe than in the case of uniform wetting but the increase in the sidelobe level is more pronounced.

A need exists for a better understanding of radome operation when its surface is wet. A limited amount of investigation of this problem has been done to date.[25,26] This problem is accentuated at millimeter wavelengths because of the sensitivity of the small wavelength. A need also exists for material development to produce coatings with a long lifetime which control the water distribution on the radome surface.

In practical designs, the radome environment must be carefully controlled to preclude water condensation. Similar care should be given to antennas without radome protection. For example, the 15 ft antenna described in Ref. 3 uses a heater system on the back side of the reflector to raise the temperature sufficiently to avoid dew condensation. This antenna is an example of a high gain antenna which operates without a radome.

B. RF COMPONENTS

The development of RF components associated with the antenna should be pursued in parallel with the antenna development. For example, mechanically scanned antennas generally require RF rotary joints to achieve scan motion. Examples of multiple channel RF rotary joint techniques for reflector antennas are described in Ref. 22. An attractive option at millimeter wave frequencies is to incorporate amplification and/or frequency conversion into the feed structure; not only are the RF losses reduced by this technique, the requirements for rotary joint operation are significantly eased. In some cases, the antenna design may be specifically selected to avoid RF rotary joints. The crosslink system used in the LES 8/9 satellite[27] used a planar reflector to steer the beam from a parabolic reflector. Another example of this design option is the triply folded horn reflector,[28] which uses rotating mechanical joints in lieu of RF rotary joints to accomplish the beam scanning.

Integrated circuit techniques for array designs naturally afford the opportunity to incorporate RF components into the antenna design. Filter, circulator, diplexer, phase shifter, coupler, polarizer, matching circuits, amplification, and frequency conversion functions can be integrated into the antenna structure. The development of devices to perform these functions requires extension beyond the designs for conventional waveguide systems. A key rationale for the integrated circuit approach is the opportunity to maximize RF efficiency and to reduce the number of interface connections to enhance reliability.

The sensitivity to RF losses in conventional waveguide runs can be reduced with oversized waveguides. This approach is limited to straight waveguide runs; bends and discontinuities excite higher order modes which can

destructively interfere with the desired mode. While the higher order TE_{01} circular waveguide mode offers the greatest potential for low loss waveguide propagation, the necessary waveguide transitions from dominant to oversize with the appropriate mode transitions are not particularly efficient. For short waveguide runs, the overall efficiency of the waveguide system may be limited by the efficiency of the transitions. An alternative is to oversize the waveguide but propagate the dominant mode rather than the higher order mode in the oversize waveguide section. This approach is described in Ref. 29, which describes a measured waveguide loss of 0.028 dB/ft over the 92-96 GHz frequency range; a conventional waveguide has a 1 dB/ft loss. Higher order mode excitation for both linear and nonlinear transition profiles was investigated and the measured insertion loss for a pair of transitions was less than 0.3 dB. Such an approach offers the opportunity to improve RF efficiency for some applications.

V. SUMMARY AND CONCLUSIONS

A wide variety of millimeter wave antenna technology demonstrations have been performed and several examples have been cited to highlight the diversity of these developments. A basic task for future efforts is to extend these developments into practical system designs to service future communication needs. Reflector and horn antenna technology have had the widest development effort followed by lens designs. Millimeter wave array antennas have had the most limited development and current research efforts are concentrating on integrated design approaches to enhance RF efficiency and reproducibility, and to minimize the number of connecting interfaces. A variety of fabrication techniques have been developed to manufacture millimeter wave antennas with the appropriate precision. As discussed, the compact physical size of millimeter wave antennas permits the design freedom to exploit techniques which would be impractical at lower frequencies.

The high degree of spatial resolution derived from compact antenna designs coupled with the wide bandwidth allocations at millimeter wavelengths affords significant opportunities to expand communication capabilities and enhance electronic survivability in future designs. Multiple beam designs on the satellite segment offer particularly high leverage opportunities to meet these objectives. Adaptive processing techniques can substantially improve interference rejection performance for a broad range of applications.

The requisite antenna development for future system applications spans several areas. In general, the development of suitable tracking systems should be pursued. Operation at widely separated frequencies, e.g., 20/44 GHz, affords the opportunity for design innovation to optimize antenna performance for both bands. The interface between antennas and electronics is particularly sensitive to RF losses. Given the present output power levels of solid-state devices, techniques for their optimum combination to achieve the desired output ERP performance will be needed for efficient operation. Antenna design techniques which minimize the dispersion that limits the bandwidth of adaptive electronics will be required to achieve adaptive

cancellation over the wide spectral allocations with minimum burden on the adaptive circuitry. The development of radome technology and a better understanding of radome operation when wet will be needed for practical applications.

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LABORATORY OPERATIONS

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